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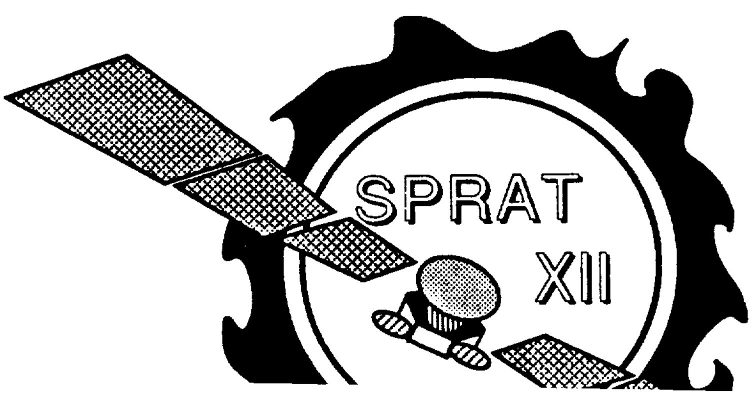
SPACE PHOTOVOLTAIC RESEARCH AND TECHNOLOGY



SPRAT XII Abstracts

NASA Lewis Research Center, Cleveland, Ohio
October 20-22, 1992

(NASA-TM-110079) TWELFTH SPACE PHOTOVOLTAIC RESEARCH AND TECHNOLOGY CONFERENCE (SPRAT 12) Abstracts Only (NASA. Lewis Research Center) 54 p

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AGENDA

Twelfth Space Photovoltaic Research and Technology Conference (SPRAT XII)

October 20-22, 1992

Tuesday, October 20

8:00 am	Registration - Administration Building Foyer Coffee and doughnuts provided
9:00	Conference Convenes Salvatore J. Grisaffe, Director, Aerospace Technology Directorate NASA Lewis Research Center

Program Reviews Session 1

Technical Session 1 - InP Solar Cells

* Abstract not available at time of printing.

Technical Session 2 - Amorphous Silicon and Thin Film Solar Cells

Wednesday, October 21

* Abstract not available at time of printing.

Thursday, October 22

Technical Session 7 - Space Environmental Effects on Solar Cells

9:30 Break

9:50 Workshop 1 Summary

10:10 Workshop 2 Summary

10:30 Workshop 3 Summary

10:50 Workshop 4 Summary

11:10 Workshop 5 Summary

11:30 Workshop 6 Summary

11:50 Concluding Remarks

IAPG SOLAR PHOTOVOLTAIC PANEL FALL MEETING

1:00-4:00 pm

Meeting to be held at the Administration Building. Room location to be posted. (Meeting restricted to government personnel).

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* Abstract not available at time of printing.

Program Reviews Session 1

NASA BASE R&T PROGRAMS ON PHOTOVOLTAIC

Toni Grobstein, NASA Headquarters

AN OVERVIEW OF THE DEFENCE RESEARCH AGENCY PHOTOVOLTAIC PROGRAM

Christopher Goodbody, DRA, England

NASDA PROGRAM ON PHOTOVOLTAIC SPACE POWER SYSTEM DEVELOPMENT

Sumio Matsudo, NASDA, Japan

Technical Session 1 - InP Solar Cells

P/11
94N11381

A Detailed Study of the Photo-injection Annealing of InP Solar Cells

R.J. Walters   Naval Research Laboratory, Washington, DC
G.P. Summers   Naval Research Laboratory, Washington, DC and University of Maryland Baltimore County

It has been reported that thermally diffused InP solar cells are extremely resistant to particle irradiation and to recover from radiation under solar illumination. Yamaguchi et al. showed cells which were irradiated with 1 MeV electrons up to 7×10^{15} cm^{-2} to operate at about 85% of the BOL power level after only one minute of photo-illumination. Despite this remarkable discovery, almost no research other than the Japanese work has been reported on these devices. Instead, recent InP solar cell research has focused on MOCVD grown devices.

The research on MOCVD cells has produced results widely different from those of Yamaguchi et al. While photo-illumination of irradiated MOCVD cells does induce defect annealing, it does not induce cell recovery. Furthermore, the minority carrier trap spectrum detected by DLTS in the irradiated MOCVD cells was significantly different from that detected by Yamaguchi et al. Since a solar cell is a minority carrier device, it is the minority carrier trapping centers which would be expected to have the largest impact on device operation. The minority carrier DLTS spectrum of irradiated MOCVD InP has been well characterized; however, this is not the case for the thermally diffused junctions. This paper focuses on this aspect of the cell behavior.

The Naval Research Laboratory has obtained several of the original Nippon Mining thermally diffused InP solar cells. The I-V characteristics and DLTS spectra of theses cells were measured before and after 1 MeV electron irradiation and after several annealing experiments. The major result is the observance of the annealing of irradiated thermally diffused cells under solar illumination. This is significant because the annealing was observed using the same equipment used to determine that the MOCVD cells did not recover under illumination. Furthermore, as shown below, it was observed that 175 K is a clear onset temperature for the annealing process. The photo-illumination annealing experiment was repeated at different temperatures, under different injection current densities, and on cells which experienced different electron fluences. Extensive DLTS measurements were made as a part of every annealing run on the actual solar cells in an attempt to characterize the minority carrier defect spectrum of these cells in terms of the annealing of the photovoltaic parameters.

The research of Yamaguchi et al. has indicated the tremendous potential of InP solar cells for space applications, but the lack of understanding of the physics of the radiation response of InP is hindering the full exploitation of InP devices. This report investigates this physics more fully in order to understand the processes involved and to stimulate more research in this area.

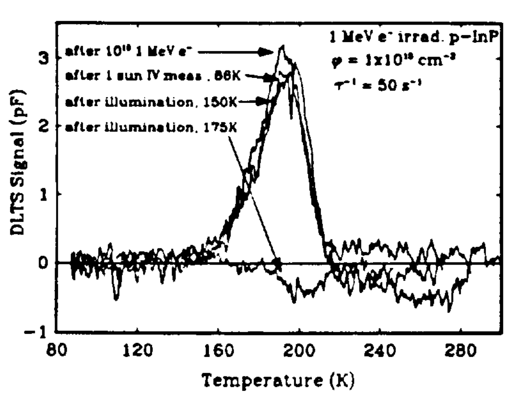

Figure 1: The annealing of the DLTS spectrum under solar illumination.

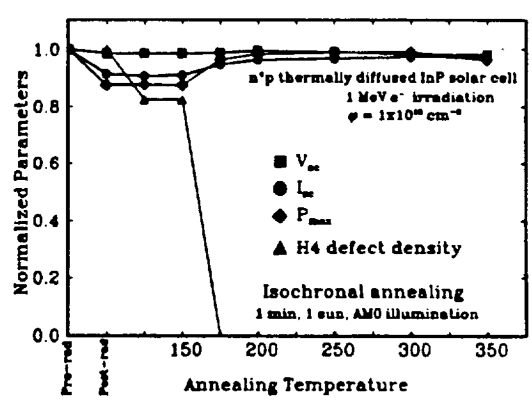

Figure 2: The annealing of the photovoltaic parameters and DLTS signal under solar illumination.

High Temperature Annealing of Minority Carrier Traps in Irradiated MOCVD n^+p InP Solar Cell Junctions

S.R. Messenger[1], R.J. Walters[2], and G.P Summers[2,3]

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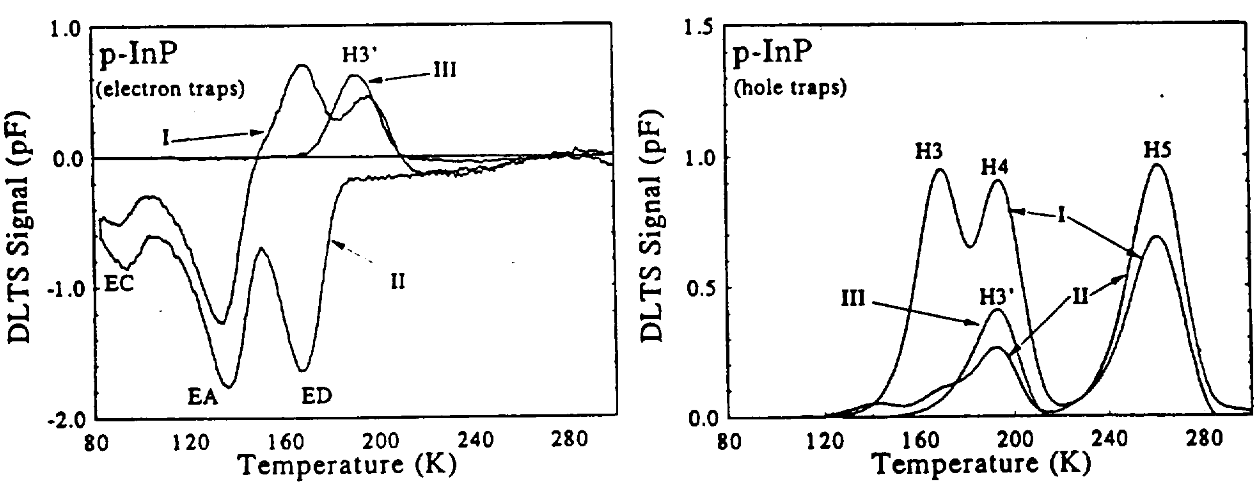
Abstract

The correlation between the annealing of the main DLTS peak H4 and the recovery of the photovoltaic I-V curves described by Yamaguchi and co-workers in irradiated, diffused junction n^+p InP solar cell junctions is not seen in MOCVD junctions. In MOCVD junctions, H4 can be reduced substantially both thermally and by injection, but only minimal recovery of the I-V curves is seen. A possible correlation between the presence of the DLTS peak H5 and solar cell degradation has been suggested for MOCVD junctions, but this is only tentative. It can be seen that the main focus of the work to date in correlating DLTS spectra and changes in photovoltaic behavior has been on the properties of hole, i.e., majority carrier traps in p-type InP. Given that minority carrier diffusion is expected to be important to efficient solar cell operation, the behavior of minority carrier traps should also be carefully measured, but these have largely been ignored until now. The introduction and annealing of these traps is the subject of this paper. The behavior of three electron traps, EA (E_a=0.24 eV), EC (E_a=0.12 eV), and ED (E_a=0.31 eV) is described, including thermal annealing up to 650 K which is sufficient to remove all minority carrier DLTS signals. Only a new center H3' then remains in the sample, H5 having also been removed. The figures below show the various annealing stages of both the electron and hole DLTS spectra. Figures 1 and 2 are the DLTS spectra obtained in a condition with and without minority carrier injection, respectively. Other details such as carrier concentration and forward bias effects will be presented in the paper.



Figures 1 & 2: Electron and hole DLTS spectra after various annealing stages: I - injection annealing only, II - subsequent thermal anneal at 500 K for 20 minutes, III - subsequent thermal anneal at 650 K for 10 minutes. The DLTS conditions are as follows: Vr=-2V, PW=50ms, RW=50/s, Vf=0V (hole traps), Vf=1V (electron traps). The dopant levels are around 2.5×10^{16} cm^{-3}.

91N 20207

Radiation Effects in Heteroepitaxial InP Solar Cells

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NASA Lewis Research Center

Cleveland, Ohio

and

C.Vargas-Aburto

Kent State University

Kent, Ohio

Heteroeptiaxial InP/GaAs solar cells were irradiated by 3 and 0.5 MeV protons and their performance, temperature dependency and carrier removal determined at each energy. The results are compared to previous 10 MeV proton irradiations and the performance of InP homojunction cells. The radiation resistances of the InP/GaAs cells were found to be significantly higher than that of the homojunction cells at all proton energies. In addition, performance, temperature dependency and carrier removal were found to be dependent on proton energy. The results are discussed in terms of dislocation densities and an experimental relation which predicts defect concentrations as a function of energy.

PROGRESS IN p^+n InP SOLAR CELLS FABRICATED BY THERMAL DIFFUSION

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‡‡Kent State University, Kent, Ohio

In SPRAT XI, we proposed that p^+n diffused junction InP solar cells should exhibit a higher conversion efficiency than their n^+p counterparts. This was mainly due to the fact that our p^+n (Cd,S) cell structures consistently showed higher V_{oc} values than our n^+p (S,Cd) structures. The highest V_{oc} obtained with the p^+n (Cd,S) cell configuration was 860 mV, as compared to the highest V_{oc} of 840 mV obtained with the n^+p (S,Cd) configuration (AMO, 25°C).

In this work, we present the performance results of our most recent thermally diffused cells using the p^+n (Cd,S) structure. We have been able to fabricate cells with V_{oc} values approaching 880 mV. Our best cell with an unoptimized front contact grid design (GS≥10%) showed a conversion efficiency of 13.4% (AMO, 25°C) without an AR coating layer. The emitter surface was passivated by a ~50Å P rich oxide. Achievement of such high V_{oc} values was primarily due to the fabrication of emitter surfaces, having EPD densities as low as 2E2 cm^{-2} and N_a-N_d of about 3E18 cm^{-3}.

In addition, our preliminary investigation of p^+n structures seem to suggest that Cd-doped emitter cells are more radiation resistant than Zn-doped emitter cells against both high energy electron and proton irradiation.

N95- 70369

Electrochemical Characterization of InP Structures

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Electrochemical (EC) techniques represent a simple and yet accurate method to characterize InP and related materials structures. With EC techniques, uncertainties in the measurements arising from factors such as surface effects, the composition and thickness of a front dead layer, the contacts, etc., can be significantly reduced when both a suitable electrolyte is used and the measuring conditions are carefully selected.

In this work, the use of photoelectrochemical techniques with InP structures is reported. The work focuses on both the characterization and the optimization of structures grown by thermal diffusion and by epitaxial methods. Characterization of the structures is done by studying the variation in the density of surface states, number of defects, and net majority carrier concentration as a function of material removed. A step-by-step optimization process of n^+p and p^+n InP structures is also described. This involves the passivation and subsequent removal of damaged layers in order to extract the performance parameters of solar cells fabricated with these structures.

ACTIVATION ENERGY AND CAPTURE CROSS SECTION OF MAJORITY CARRIER TRAPS IN Zn DOPED InP

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PHOTOVOLTAICS BRANCH NASA LEWIS RESEARCH CENTER

* DEPARTMENT OF MATERIALS SCIENCE AND ENGINEERING
CASE WESTERN RESERVE UNIVERSITY

Schottky barrier diodes were fabricated on Zn doped InP wafers. The diodes were radiation damaged with 2 MeV protons to a dose of $2 \times 10^{12}/cm^2$. The damage was analyzed by DLTS (deep level transient spectroscopy) using the double correlation technique. Capture cross sections were measured directly using the pulse width variation technique.

Two major defects were observed in the DLTS spectra. The first defect, located at Ev + 0.31 eV, is the defect H4. A direct measurement of its capture cross section was made and a value of 9.1×10^{-18} cm^2 obtained. The second defect, observed at Ev + 0.52 eV, is the defect H5. The capture cross section of H5 varied with temperature, as described by the relationship $\sigma = \sigma_o \exp^{-\Delta E/kT}$ where $\sigma_o = 1.8 \times 10^{-19}$ cm^2 and $\Delta E = .08$ eV. This relationship yields a $\sigma = 8.2 \times 10^{-21}$ cm^2 at room temperature.

The surprisingly small capture cross section of H5 is discussed in terms of a two step process for carrier capture at the defect. The two step model also predicts the temperature dependence of the capture cross section.

The advantages of the improved experimental techniques used are also discussed.

P/A
94N 11327

EFFECTS OF SOLAR CELL ENVIRONMENT ON CONTACT INTEGRITY

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The III-V semiconductors react extremely rapidly with most commonly used contact metallizations. This precludes the use of elevated temperatures in the contact formation process for solar cells and other shallow junction devices. These devices must rely upon contact metallizations that are sufficiently conductive in their "as-fabricated" state. However, while there are a number of non-sintered metallizations that have acceptable characteristics, the lack of a sintering step makes them vulnerable to a variety of environmentally induced degradation processes. This paper describes the degrading effects resulting from the exposure of unsintered devices to a humid environment and to a vacuum (space) environment. It is shown, further, that these effects are magnified by the presence of mechanical damage in the contact metallization. The means to avoid or prevent these degrading interactions are presented.

MEASUREMENT OF THE MINORITY CARRIER DIFFUSION LENGTH AND EDGE SURFACE-RECOMBINATION VELOCITY IN InP

N/A

94N11304

Roshanak Hakimzadeh[1,2] and Sheila G. Bailey[3]

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ABSTRACT

A scanning electron microscope (SEM) was used to measure the electron (minority carrier) diffusion length (L_n) and the edge surface-recombination velocity (V_s) in zinc-doped Czochralski-grown InP wafers. Electron-beam-induced current (EBIC) profiles were obtained in specimens containing a Schottky barrier perpendicular to the scanned (edge) surface. An independent technique was used to measure V_s, and these values were used in a theoretical expression for normalized EBIC. A fit of the experimental data with this expression enabled us to determine L_n.

We observed an unexpected effect which prevented us from measuring L_n in the lower doped (2×10^{16} cm^{-3}) specimens. The interaction of the electron beam with the native oxide resulted in an inversion layer near the surface which in turn resulted in charge collection with approximate unity efficiency up to hundreds of micrometers from the Shottky barrier. Hence, The resultant EBIC profiles did not decay very much even at large distances (x) from the Schottky barrier. In the higher doped (1×10^{18} cm^{-3}) specimens, the EBIC profiles decayed with increasing x, as expected. V_s and L_n were measured as a function of x in these specimens. The results were that V_s varied between 40.86 cm/sec and 1.80×10^3 cm/sec, and L_n ranged from 0.25 μm to 1.36 μm.

Surface Passivation of InP Solar Cells with InAlAs Layers

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*Sverdrup Technology Inc., Brook Park, OH 44142

The resistance of indium phosphide (InP) cells to electron and proton irradiations, and its prospects for high efficiency make these cells very promising for space applications. The efficiencies of InP cells produced to date are limited due to high values of surface recombination velocity (~10^7 cm/s), which could be reduced by proper passivation/window layers. However a suitable material does not exist. This work investigates wide-bandgap lattice-matched InAlAs as a passivation layer in InP solar cells. Preliminary results of our investigations have been published elsewhere. Our calculations using the PC-1D numerical code have shown that the use of InAlAs layer improves p^+n cell efficiencies, but no appreciable improvements have been seen for n^+p cells. The improvement in p^+n InP cell efficiency is due to the discontinuity in the conduction band energy at the InAlAs/InP heterojunction. The InAlAs layer acts as a minority carrier mirror and confines the minority carriers in the cell emitter region. This results in effectively reducing the surface recombination. We consider two designs in this work: a baseline design which represents the currently available cell technology and an optimized cell design, which we hope could be achieved in the future by material and cell process improvements. The baseline and optimized cell efficiency improves to 20% and 23% respectively with 10 nm InAlAs layer, from 14.7% and 15.4% AM0 without the InAlAs layer. The greater improvement of the optimized cell is due to its improved bulk recombination as compared to baseline cell. Cell efficiency as a function of InAlAs layer thickness has been studied. Thicker InAlAs layers degrade cell performance due to strong absorption. The calculated quantum efficiency results show the improvement in blue response with InAlAs layers. These results show that the InAlAs is a promising passivation/window layer material for p^+n InP cells. The effect of lattice mismatched InAlAs layers will also be discussed.

N95- 70370

Three-dimensional Numerical Modeling of Indium Phosphide Point-contact Solar Cells

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Abstract

The Point-Contact Solar Cell (PCSC) geometry has proven very effective for silicon cells. To date, it has not been implemented in III-V materials. In addition, modeling such a geometry is very difficult because of its three-dimensional nature. We have developed a three-dimensional finite element modeling code (FIESTA ROC). In this paper, we present results from a three-dimensional modeling study of InP point-contact solar cells.

Technical Session 2 - α-Si & Thin Film Solar Cells

1411/1210

POLYIMIDE BASED AMORPHOUS SILICON SOLAR MODULES

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Ames, Iowa

Requirements for space power are increasingly emphasizing lower costs and higher specific powers. This results from new fiscal constraints, higher power requirements for larger applications and the evolution toward longer distance missions such as a Lunar or Mars base. The polyimide based a-Si modules described in this paper are being developed to meet these needs. The modules consist of tandem a-Si solar cell material deposited directly on a roll of polyimide. A laser scribing/printing process subdivides the deposition into discrete cell strips which are series connected to produce the required voltage without cutting the polymer backing. The result is a large, monolithic, blanket type module approximately 30 cm wide and variable in length depending on demand. Current production modules have a specific power slightly over 500 W/Kg with room for significant improvement. Costs for the full blanket modules range from $30/Watt to $150/Watt depending on quantity and engineering requirements. Work to date has focussed on the modules themselves and adjusting them for the AM0 spectrum. Work is needed yet to insure that the modules are suitable for the space environment.

This work is partially sponsored by NASA Lewis Research Center under contract # NAS3-26244

1/A

94N 11391

INVESTIGATION OF THE RADIATION RESISTANCE OF TRIPLE-JUNCTION a-Si ALLOY SOLAR CELLS IRRADIATED WITH 1.00 MeV PROTONS*

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The effect of 1.00 MeV proton irradiation on triple-junction a-Si:H alloy solar cells is reported for the first time. Thirty-six cells were designed and fabricated by a vendor, and delivered with contact pads ready for testing. The cells were fabricated on tin oxide coated 0.020" glass superstrates using plasma enhanced chemical vapor deposition. The bottom contacts on the cells were indium tin oxide and silver layers. Laser scribes were employed by the vendor to isolate test cells out of large-area cells. The test cells had active areas of 0.35 cm^2 and were 1.0 by 2.0 cm^2. Using a fill-factor criterion of 0.60, twenty-seven cells survived initial testing in our laboratory. Initial tests included probe contacting to measure light and dark current-voltage characteristics of cells "as received" and annealed. Six cells were used to investigate the effect of multiple annealing cycles on the cell parameters. The effect of ten temperature cycles between room temperature and 200 °C with a two-hour soaking time was found to be insignificant after the first annealing cycle. Three cells were studied by Rutherford Backscattering Spectrometry and RUMP simulations to determine the structure of the cells, and the thicknesses of the tin oxide layer and the indium tin oxide/silver layers. TRIM simulations of the proton energy loss in the indium tin oxide/silver contact were carried out to determine an irradiating proton energy which would insure the active volume of cells was degraded with 1.00 MeV protons. Eighteen cells were irradiated and three cells were used as controls. Three cells were irradiated at each of six fluences between 5.10E12 and 1.46E15 cm^{-2}. The irradiations produced reductions in the average of the cell peak power ranging from 0.920 to 0.015 for fluences between 5.10E12 and 1.46E15 cm^{-2}, respectively. The presentation will describe the investigations of the radiation resistance of triple-junction a-Si:H alloy solar cells. The degradation mechanisms will be discussed using the effect of proton irradiation on cell open-circuit voltage, short-circuit current and fill factor, and the results of our earlier investigations.

* Supported by NASA under Grant 3-833 and the TRW Engineering & Test Division.

Results of Some Initial Space Qualification Testing on Triple Junction α-Si and $CuInSe_2$ Thin Film Solar Cells

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ABSTRACT

A series of electron and proton irradiations have been completed on one type of Triple Junction α-Si and two types of $CuInSe_2$ thin film solar cells. Electron energies of 0.7, 1.0 and 2.0 MeV were used when exposing the cells to incremental fluences of $3X10^{13}$, $1X10^{14}$, $3X10^{14}$, $1X10^{15}$, $3X10^{15}$ and $1X10^{16}$ electrons/cm^2. Proton energies of 0.115, 0.24, 0.3, 0.5, 1.0 and 3.0 MeV were used when exposing the cells to incremental fluences of $1X10^{9}$, $1X10^{10}$, $1X10^{11}$, $1X10^{12}$ and $2X10^{12}$ protons/cm^2. As expected, the cells are very resistant to electron and proton irradiation. However, when a selected cell type is exposed to low energy protons designed to penetrate to the junction region, there is evidence of more significant damage. Following several of the larger fluences, the cells were subjected a series of annealing experiments at temperatures between 20°C and 60°C. A significant amount of annealing was observed in several of the cells. However, it is not permanent and durable, but merely a temporary restoration, later nullified with additional irradiation. Cell contact pull strength tests were conducted on the Triple Junction α-Si cells, 667 grams, and one of the two types of $CuInSe_2$ cells, 880 grams. These cells have also been subjected to a 500 hour photon degradation test. The results reveal that one of the $CuInSe_2$ cell types did not degrade under photon illumination, but the photons caused a power degradation of more than 20% in the other $CuInSe_2$ cell and in the Triple Junction α-Si cell.

Acknowledgements

The research described in this paper was carried out by the Jet Propulsion Laboratory, California Institute of Technology, and was sponsored by the United States Air Force Phillips Laboratory through an agreement with the National Aeronautics and Space Administration.

Flexible Polycrystalline Thin-Film Photovoltaics for Space Applications*

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Polycrystalline thin-film photovoltaics (PV), such as CIS and CdTe, have received considerable attention recently with respect to space power applications. Their combination of stability, efficiency, and economy from large-scale monolithic integration of modules can have significant impact on cost and weight of PV arrays for spacecraft and planetary experiments. An added advantage, due to their minimal thickness (≈ 6 μm *sans* substrate), is the ability to manufacture lightweight, flexible devices (≈ 2000 W/kg) using large-volume manufacturing techniques. In this paper, the photovoltaic effort at Martin Marietta and ISET will be discussed, including large-area, large-volume thin-film deposition techniques such as electrodeposition and rotating cylindrical magnetron sputtering. Progress in the development of flexible polycrystalline thin-film PV will be presented, including evaluation of flexible CIS cells. In addition, progress on flexible CdTe cells will be presented. Finally, examples of lightweight, flexible arrays and their potential cost and weight impact will be discussed.

* *This work performed under Martin Marietta IR&D D-17R, "Photovoltaic Technologies"*

Program Reviews Session 2

AIR FORCE PROGRAMS ON SPACE PHOTOVOLTAIC

Air Force

DOE PROGRAMS FOR SPACE POWER

Department of Energy Office of Space Power

Technical Session 3 -
Laser Power Converters

X

S2-44

P-1

InGaAs Concentrator Cells for Laser Power Converters and Tandem Solar Cells

Steven J. Wojtczuk, Stanley M. Vernon and Edward D. Gagnon
Spire Corporation, Bedford, MA

$In_{0.53}Ga_{0.47}As$ photovoltaic cells are useful for 1.315μm laser energy conversion and as the bottom cells of InP/InGaAs tandem solar cells. One-sun and 100-sun AM0 efficiency (Table 1), quantum efficiency (Fig.1), and log IV dark current data were measured for single-junction N-on-P InGaAs concentrator cells with and without InP windows grown by metal organic chemical vapor deposition (MOCVD) on InP substrates. Lattice mismatch between the InGaAs epilayers and InP substrate, as measured by X-ray diffractometry, is also reported, since, although small, the mismatch affects the dark current and efficiency.

Table 1
AM0 Efficiency Data for Best InGaAs n/p Cells

Voc V	Jsc mA/cm²	AM0 Suns	Fill %	Eff %
With InP window; mismatch of 790ppm				
0.287	57.21	1	57.1	6.83
0.484	5074.80	88.7	66.8	13.5
No Window ; mismatch of 280ppm				
0.305	45.40	1	70.8	7.14
0.439	4825.0	106	65.8	9.57

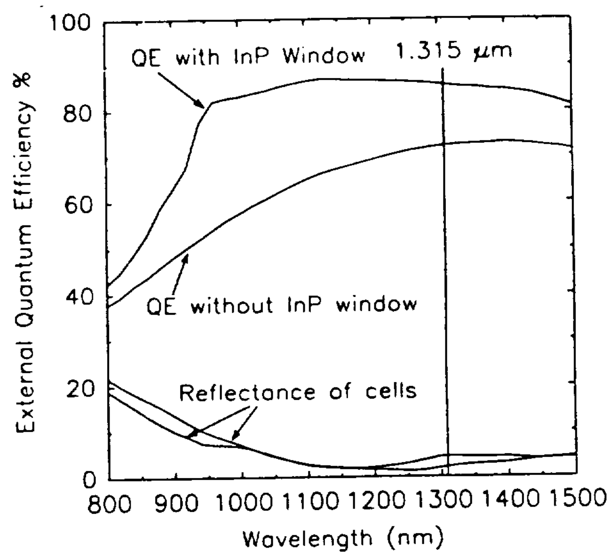

Fig.1 External quantum efficiencies

The 1.315μm laser power conversion efficiency was estimated at 29.4% (at 5.57 W/cm²). We assumed an incident 1.315μm laser power density of 5.57 W/cm² because the measured external quantum efficiency of 86% at 1.315μm gives a short-circuit photocurrent of 5.07 A/cm² with this value of laser power. Measured AM0 concentration data at this same current density in Table 1 should also accurately give the cell open-circuit voltage V_{OC} (484mV) and fill-factor (66.8%) under the laser illumination. These values were then used to estimate the efficiency.

Theoretical estimates of $In_xAl_yGa_{1-x-y}As$ photovoltaic cells under development will be presented. The bandgap of these cells more closely matches the 0.94eV photon energy of the 1.315 μm laser radiation, increasing the power conversion efficiency at 1.315μm.

Photovoltaic Cells for Laser Power Beaming

N95- 70371

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Laser beaming of power from Earth to space using a photovoltaic array as a laser power converter could be an extremely useful technology, with applications to space missions from low Earth orbit to a lunar base. Extremely high average-power lasers would be required, with laser power ranging from hundreds of kilowatts to several magawatts, in a wavelength range of ~700-1000 nm. The most likely candidate for such a laser is the free-electron laser (FEL). However, free electron lasers inherently operate in a pulsed format. The output of a proposed induction FEL, for example, consists of a continuous string of pulses of approximately fifty nanosecond pulse width, and a 1:1000 duty factor. Existing solar cells are not well designed to respond to pulsed incident power.

Three main effects decrease the efficiency of a solar cell under pulsed laser illumination: series resistance, L-C "ringing" with the output circuit, and current limiting due to the output inductance.

Solutions to the problems can be divided into two catagories: changing the pulse shape (i.e., using a different format of laser, or stretching the pulse-length with an optical cavity), or designing a solar cell to accept the pulsed input. In this paper approaches to redesigning the solar cell will be discussed.

To better understand cell response to pulsed illumination at high intensity, the PC-1D cfinite-element omputer model was used to analyze the response of solar cells to pulsed laser illumination. Over 50% efficiency was calculated for both InP and GaAs cells under steady-state illumination near the optimum wavelength. The time-dependent response of a high-efficiency GaAs concentrator cell to a laser pulse was modelled, and the effect of laser intensity, wavelength, and bias point was studied.

Designing a cell to accomodate pulsed input can be done either by accepting the pulsed output and designing a cell to minimize adverse effects due to series resistance and inductance, or to design a cell with a long enough minority carrier lifetime, so that the output of the cell will not follow the pulse shape. Two such design possibilities are a monolithic, low-inductance voltage-adding GaAs cell, or a high-efficiency, light-trapping silicon cell. The advantages of each design will be discussed.

A monolithic series-interconnected cell, in which a wafer has many individual sub-cells connected electricaly in series, has increased voltage and decreased current over a single-junction cell. The electrical series resistance losses are reduced substantially. For pulsed laser illumination, the voltage adding design has several additional advantages. Series-connecting cells allows use of a blocking diode to truncate the reverse-current portion of LC oscillations. Further, the series connection has reduced junction capacitance over a single cell of the same area, and by connecting subcells in series, inductive back voltage is divided between subcells.

The other approach is use of a high-efficiency silicon cell with enhanced radiation tolerance and red response. Existing silicon cells used in space use technology developed in the late 1970s. While the efficiency of currently-used silicon cells is 13 to 14%, over 20% efficiency has been achieved in the laboratory.

Silicon is an indirect bandgap semiconductor. This means that the minority carrier lifetime is high, but the optical absorption coefficient is low. The low optical absoption means that silicon becomes nearly transparent to light near the bandgap, the range where laser conversion is most efficient. The solution is to increase the optical pathlength within the cell. Light trapping allows a solar cell to be made thin without loss of light-generated current. Thin cells are extremely radiation tolerant.

A high-voltage design will minimize temperature coefficient. High voltage is needed for high efficiency as well. This will require a fully surface-passivated design. Such a thin, high-efficiency radiation tolerant silicon cell will have other applications: a solar cell for ultra-light-weight space solar arrays, as well as an excellent low-bandgap element of high-efficiency tandem cell.

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The Efficiency of Photovoltaic Cells Exposed to Pulsed Laser Light

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Future space missions may use laser power beaming systems with a free electron laser (FEL) to transmit light to a photovoltaic array receiver. To investigate the efficiency of solar cells with pulsed laser light, several types of GaAs, Si, $CuInSe_2$, and GaSb cells were tested with the simulated pulse format of the induction and radio frequency (RF) FEL. The induction pulse format was simulated with an 800-watt average power copper vapor laser and the RF format with a frequency-doubled mode-locked Nd:YAG laser. Averaged current vs bias voltage measurements for each cell were taken at various optical power levels and the efficiency measured at the maximum power point.

Experimental results show that the conversion efficiency for the cells tested is highly dependent on cell minority carrier lifetime, the width and frequency of the pulses, load impedance, and the average incident power. Three main effects were found to decrease the efficiency of solar cells exposed to simulated FEL illumination: cell series resistance, LC "ringing", and output inductance. Improvements in efficiency were achieved by modifying the frequency response of the cell to match the spectral energy content of the laser pulse with external passive components.

94N11376

ABSTRACT:

RESPONSE OF SILICON SOLAR CELL TO PULSED LASER ILLUMINATION

Authors:

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National Aeronautics and Space Administration
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This paper deals with the response of silicon solar cell(s) to pulsed laser illumination. The motivation for this work was due to the interests of earth to space/moon power beaming applications. When this work began it was not known if solar cells would respond to laser light with pulse lengths in the nanosecond range and a repetition frequency in the KHz range. The is because the laser pulse would be shorter than the minority carrier lifetime of silicon. A 20 ns FWHM (Full Width Half Max) pulse from an aluminum-gallium/arsenide (AlGaAs) diode laser was used to illuminate silicon solar cells at a wavelength of 885 nanometers. Using a high speed digital oscilloscope the response of the solar cells to individual pulses across various resistive loads was observed and recorded.

Technical Session 4 -
Solar Cell & Array Technology

94N11673

EOL PERFORMANCE COMPARISON OF GaAs/Ge AND Si BSF/R SOLAR ARRAYS

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EOL power estimates for solar array designs are significantly influenced by the predicted degradation due to charged-particle radiation. This paper presents new radiation-induced power degradation data for GaAs/Ge solar arrays applicable to missions ranging from low earth orbit (LEO) to geosynchronous earth orbit (GEO) and compares these results to silicon BSF/R arrays. These results are based on recently published radiation damage coefficients for GaAs/Ge cells (1).

GaAs/Ge solar cells have significant advantages over silicon cells for space-based solar arrays:

> The efficiency (BOL, AM0, 28°C) of space-qualified, production-grade, MOCVD-grown GaAs/Ge cells is greater than 18%, compared to less than 15% for conventional silicon cells and less than 16% for textured silicon cells.
>
> The Pmax temperature coefficient for GaAs/Ge is more favorable than the value for silicon.
>
> For almost all missions, GaAs/Ge cells are more resistant to radiation-induced power degradation than silicon cells.

This degradation is typically established by first converting the proton and electron spectra associated with an orbit to an equivalent fluence of 1 MeV electrons and then assigning a degradation value based on 1 MeV electron radiation data for the cell type of interest. This methodology is used to determine the radiation-induced power degradation results presented in this paper.

The power density ratio (GaAs/Ge to Si BSF/R) has been found to be as high as 1.83 for the proton-dominated worst-case altitude of 7408 km (MEO). Based on the EOL GaAs/Ge solar array power density results for MEO, missions which were previously considered infeasible may be reviewed based on these more favorable results.

The additional life afforded by using GaAs/Ge cells is an important factor in system-level trade studies when selecting a solar cell technolgy for a mission and needs to be considered. The data presented in this paper supports this decision since the selected orbits have characteristics similar to most orbits of interest.

1. B.E. Anspaugh, "Proton and Electron Damage Coefficients for GaAs/Ge Solar Cells," 22nd IEEE Photovoltaic Specialists Conference, p.1593, 1991.

N94-11397

A HIGH SPECIFIC POWER SOLAR ARRAY FOR LOW TO MID-POWER SPACECRAFT

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B. S. Smith, Spectrolab Inc

Abstract

UltraFlex is the generic term for a solar array system which delivers on-orbit power in the 500 to 5,000 watt per wing sizes with end of life specific power performance of 130 to 160 watts per kilogram. Such performance is accomplished with off-the-shelf silicon cells and state-of the-art materials and processes.

Much of the recent work in photovoltaics is centered on advanced solar cell development. Successful as such work has been, there has not emerged an integrated solar array system which meets the NASA stated goals of "increasing the end-of-life performance of space solar cells and arrays while minimizing their mass and cost". Here we address the other issues. That is: Is there an array design that satisfies the usual requirements for space rated hardware and is inherently reliable, inexpensive, easily manufactured and simple, which can be used with both advanced cells currently in development as well as with inexpensive silicon cells? The answer is yes.

The UltraFlex system described below incorporates use of a blanket substrate which is thermally compatible with silicon and other materials typical of advanced multi-junction devices. Through judicious material choice the blanket is intrinsically insensitive to atomic oxygen degradation. It is composed of space rated materials and is compatible with standard cell bonding processes. The deployment mechanism is simple and reliable and the structure is inherently stiff (high natural frequency). Mechanical vibration modes are also readily damped.

The basic design is presented as well as supporting analysis and component tests.

-4N1-22

TAB Interconnects for Space Concentrator Solar Cell Arrays

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The Boeing Company has evaluated the use of Tape Automated Bonding (TAB) and Surface Mount Technology (SMT) for a highly reliable, low cost interconnect for concentrator solar cell arrays. TAB and SMT are currently used in the electronics industry for chip interconnects and printed circuit board assembly.

TAB tape consists of sixty-four 3 Mil/1 Oz tin plated copper leads on 8 mil centers. The leads are thermocompression gang bonded to GaAs concentrator solar cell with silver contacts. This bond, known as an Inner Lead Bond (ILB), allows for pretesting and sorting capability via nondestruct wire bond pull and flash testing. Destructive wire pull tests have resulted in preferred mid-span failures. Improvements in fill factor have been attributed to decreased contact resistance on TAB bonded cells.

Preliminary thermal cycling and aging tests have shown excellent bond strength and metallurgical results. Auger scans of bond sites reveals an Ag-Cu-Tin composition. Improper bonds are identified through flash testing as a performance degradation. On going testing of cells are underway at Lewis Research Center.

SMT techniques are utilized to excise and form TAB leads post ILB. The formed leads' shape isolates thermal mismatches between the cells and the flex circuit they are mounted on.

TABed cells are picked and placed with a gantry x-y-z positioning system with pattern recognition. Adhesives are selected to avoid thermal expansion mismatch and promote thermal transfer to the flex circuit.

TAB outer lead bonds are parallel gap welded (PGW) to the flex circuit to finish the concentrator solar cell subassembly.

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Space Station Freedom Advanced Photovoltaic and Battery Technology Development Planning

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Space Station Freedom (SSF) is expected to provide 75 kW of usable electrical power shortly after Permanently Manned Capability (PMC) in 1999. This power will be provided by planar silicon arrays and nickel-hydrogen batteries. The need for usable power is envisioned to grow to as much as 150 kW during SSF's 30-year evolutionary design life. Photovoltaic and battery technology can be expected to achieve significant advancements prior to the beginning of the evolutionary phase.

Plans for developing the most promising photovoltaic and battery technologies have been prepared in a study funded by NASA Langley Research Center. Emphasis in the study was placed on the SSF evolution application. These technologies could benefit other applications as well, including upgrade of original SSF equipment or other low Earth orbit platforms.

This paper summarizes the accomplishments of the six-month NASA study. Described in the paper are (1) the current state of the art of photovoltaic and battery technology, (2) projected application of technologies to meet the needs of an evolutionary SSF, (3) the most cost effective technologies meeting SSF evolution needs, and (4) roadmaps describing paths for maturing these technologies with focus on the SSF evolution application.

Recent Developments in Refractive Concentrators for Space Photovoltaic Power Systems

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Since SPRAT XI, significant progress has been made in the development of refractive concentrators for space photovoltaic arrays. Advances have been made in four key areas:

1. Mini-Dome Fresnel Lens Concentrators
2. Silicone Prismatic Cell Covers
3. All-Glass Prismatic Cell Covers
4. Line-Focus Fresnel Lens Concentrators

In the first area, a production run of several hundred silicone mini-dome lenses has been performed. Twelve of these lenses are incorporated into the Boeing/NASA mini-dome lens/tandem cell array on the PASP Plus Flight Experiment, which is scheduled for launch in early 1993. Manufacturing processes have been developed and verified for making consistent, high-performance (90% uncoated net optical efficiency) silicone lenses. Cost-effective approaches for molding parquets of mini-dome lenses have also been identified for future large-scale array production.

In the area of cell covers, 3M has developed a mass-production process for making silicone prism covers for solar cells. This continuous process provides excellent quality covers at very low cost. The next planned step in the silicone prism cover development is to equip the covers with pressure sensitive adhesive (PSA) for ease of application to the solar cell. As part of the SBIR program, GELTECH, working with ENTECH, has successfully made high-quality all-glass prism covers via the sol-gel casting process.

In the fourth area, work has begun on a manufacturable, low-cost, line-focus space photovoltaic concentrator array. The new array will use an arched linear Fresnel lens, which has the same optical attributes as the mini-dome lens (maximal transmittance and error tolerance), but which is manufacturable via a continuous process. In addition, the silicone linear lens is easy to laminate to a microglass superstrate (for protection against atomic oxygen and ultraviolet radiation) and requires only one critical axis of sun-tracking.

94N-703

NEW EXPERIMENTAL TECHNIQUES FOR SOLAR CELLS

Ron Lenk, Principal Engineer, Space Systems/Loral, Palo Alto, CA.
Abstract of a paper to be presented at
the 12th Space Photovoltaic Research and
Technology Conference,
NASA Lewis Research Center,
Cleveland, Ohio
October 20-22, 1992

Experimental measurements of solar cell capacitance in the past have shown disagreements by orders of magnitude. I show that correct measurements depend on the excitation voltage being less than the thermal voltage. Illustrative measurements taken on a cell as a function of load and temperature are shown, using two essentially different methods: 1) The slope of the impedance as a function of frequency defines the capacitance; 2) A resonance frequency between the capacitance and cabling inductance is used with the known cable inductance. The two methods yield data in close agreement with each other. The data is shown to be well-fitted by theoretical expressions. Two effective capacitances are defined for cells undergoing large fast voltage variations, such as in a shunting system : 1) The charge effective capacitance is a linear capacitor storing the same charge as the non-linear capacitance, defined by

$$C_Q(V) = \frac{1}{V} \int_0^V C(V)\, dV$$

and 2) The energy effective capacitance is a linear capacitor storing the same energy as the nonlinear capacitance, defined by

$$C_E(V) = \frac{2}{V^2} \int_0^V C(V) * V\, dV.$$

They may be used for calculating conducted emissions and energy dissipation in the shunting element, respectively.

Technical Session 5 -
Heteroepitaxial Solar Cells

Radiation Effects in $Ga_{0.47}In_{0.53}As$ Solar Cells

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G.P. Summers, Naval Research Laboratory and University of Maryland Baltimore County
S.R. Messenger SFA, Inc., Landover, MD

To develop a high efficiency, radiation hard power system for space applications, the National Renewable Energy Laboratory has produced a monolithic, two-junction $InP/Ga_{0.47}In_{0.53}As$ tandem solar cell. This paper reports results of the radiation testing of these cells by the Naval Research Laboratory. In the last InP and Related Materials Conference (Rhode Island, April 1992), the radiation response of the InP top cell was shown to be identical to that of the shallow homojunction InP cells. This is very encouraging since the homojunction cells are known to be extremely radiation resistant. Therefore, the present research has concentrated on optimizing the $Ga_{0.47}In_{0.53}As$ bottom cell for radiation hardness.

This paper reports the effect of irradiating $Ga_{0.47}In_{0.53}As$ with 1 MeV electrons. Deep Level Transient Spectrometry (DLTS) and both dark and illuminated (1 sun, AM0) I-V measurements have been made over the range 100K < T < 450K. As shown below, fits of the dark I-V data to the two term diode equation were made from which the diffusion and recombination terms were determined as function of fluence. The recombination component of the dark current increased linearly with fluence. The DLTS detected two radiation-induced defect levels, one shallow (E_c-0.10 eV) and one near mid-gap (E_c-0.29 eV). Temperature coefficients of the photovoltaic parameters are presented which follow the same general behavior as other solar cell materials (e.g. Si and GaAs). However, a sharp decrease in the short circuit current is observed above ≈ 375 K. This temperature is reduced by irradiation. The radiation-induced degradation of the open circuit voltage is shown to be accurately predicted from the dark I-V measurements. The results of isochronal thermal annealing are shown below. Recovery in the photovoltaic parameters at ≈ 400 K was seen to coincide with an annealing stage of the near mid-gap defect level and a reduction in the junction dark current.

These radiation results are again encouraging. The indication is that an analytical model, using the dark I-V parameters and defect introduction rates as inputs, can be developed which will accurately predict the degradation of the $Ga_{0.47}In_{0.53}As$ photovoltaic parameters in orbit. Also, since $Ga_{0.47}In_{0.53}As$ anneals close to 400 K, on orbit annealing at near normal operating temperatures should significantly prolong the cell life.

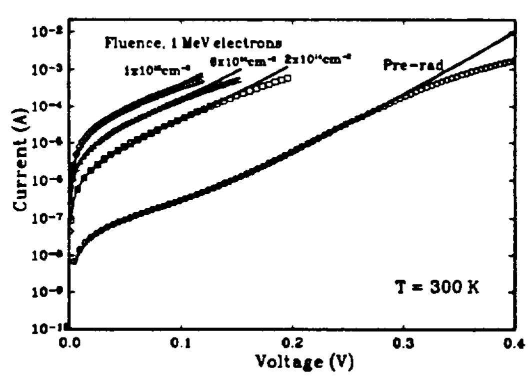

Figure 1: The effect of 1 MeV electron irradiation on the dark I-V characteristics of the $Ga_{0.47}In_{0.53}As$. The solid lines indicate the fits to the data.

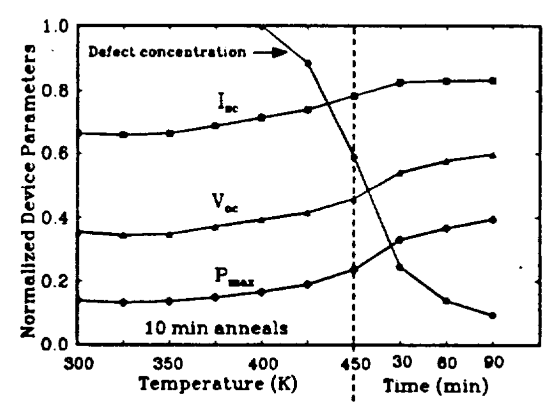

Figure 2: The results of thermally annealing an irradiated $Ga_{0.47}In_{0.53}As$ solar cell.

74N14-15

INVESTIGATION OF ZnSe-COATED SILICON SUBSTRATES FOR GaAs SOLAR CELLS

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Studies are being carried out to determine the feasibility of using ZnSe as a buffer layer for GaAs solar cells grown on silicon. This study was motivated by reports in the literature indicating ZnSe films had been grown by MOCVD onto silicon with EPD values of $2x10^5$ cm^{-2}, even though the lattice mismatch between silicon and ZnSe is 4.16 %. These results combined with the fact that ZnSe and GaAs are lattice matched to within 0.24 % suggest that the prospects for growing high efficiency GaAs solar cells onto ZnSe-coated silicon are very good. Work to date has emphasized development of procedures for MOCVD growth of ZnSe onto (100) silicon wafers, and subsequent growth of GaAs films on ZnSe/Si substrates. ZnSe and GaAs films are grown at WSU with a SPIRE 500XT reactor. ZnSe is grown by reacting H_2Se with a zinc adduct, namely, an adduct formed by mixing dimethylzinc with triethylamine. In order to grow high quality single crystal GaAs with a (100) orientation, which is desirable for solar cells, one must grow single crystal (100) ZnSe onto silicon substrates. We have found that it is straight forward to grow polycrystalline ZnSe or (111) ZnSe onto (100) silicon, but not so straight forward to obtain (100) ZnSe. Recently, a process for growth of (100) ZnSe onto (100) Si was developed. ZnSe films are grown at 450°C with a two step growth procedure. Single crystal, (100) GaAs films have been grown onto the (100) ZnSe/Si substrates that are adherent and specular. The GaAs films are not yet of adequate quality for solar cell fabrication, however. Information from TEM studies will be utilized to determine required adjustments in GaAs growth parameters such that GaAs films can be attained that are appropriate for high efficiency cell fabrication. Characterization of GaAs/ZnSe/Si film structures with TEM is now underway.

11140

Heteroepitaxial InP, and ultrathin, directly glassed, GaAs III-V Solar Cells.

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Abstract:

The commercial application of Indium Phosphide solar cells in practical space missions is crucially dependant upon achieving a major cost reduction which could be offered by heteroepitaxy on cheaper, more rugged substrates. Futhermore, significant mass reduction, compatibility with mechanically stacked multijunction cells, and elimination of the current loss through glue discoloration, is possible in III-V solar cells by the development of ultrathin, directly glassed cells.

This paper describes the progress of a UK collaborative program to develop high efficiency, homojunction InP solar cells, grown by MOCVD on Si substrates. Results of homoepitaxial cells (>17% 1 Sun AM0) are presented, together with progress in achieving low dislocation density heteroepitaxy.

Also, progress in a UK program to develop ultrathin directly-glassed GaAs cells is described. Ultrathin (5 micron) GaAs cells, with 1 Sun AM0 efficiencies up to 19.1%, are presented, together with progress in achieving a direct (glueless) bond between the cell and coverglass. Consequential development to, for example, cell grids, are also discussed.

Part of this work has been carried out with the support of the Procurement Executive, Ministry of Defence.

Technical Session 6 -
Non-Photovoltaic Energy Conversion

94N 11451

REVIEW OF BETAVOLTAIC ENERGY CONVERSION

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Betavoltaic energy conversion refers to the generation of power by coupling a beta source to a semiconductor junction device. This paper briefly reviews the theory of betavoltaic energy conversion, past studies in the field and discusses recent studies by the authors.

Principles Of Betavoltaic Energy Conversion – Many of the issues important to solar cell design are also important to the design of betavoltaic cells. However, the much lower level of excitation energy available from useful beta sources requires careful attention to cell characteristics that are relatively unimportant for solar cells. Concurrently, radiation damage resulting from energetic beta particles must be minimized to maintain an adequate power source lifetime. The I-V characteristics of a betavoltaic cell can be written in a similar manner to those for a solar cell. Additionally, one can calculate the limiting efficiency of a betavoltaic system versus bandgap [1]. The calculated limiting efficiency for several beta sources will be presented. Selection of a beta source/semiconductor combination is of course one of the key issues in betavoltaic power source design. Two important parameters are the beta source half-life τ and the maximum beta particle energy E_{max}. Selection of τ involves a trade off between long-life and beta flux magnitude. In general, one prefers the value of E_{max} to be less than the radiation damge threshold in the semiconducting materal, which is typically in the range of 150 to 400 keV. These considerations limit the choice of beta sources. These issues will be discussed.

Past Betavoltaic Studies – The first significant work in betavoltaics was carried out by Rappaport, Loferski and others at RCA in the late 1950's [2]. Si, Ge and GaAs devices were coupled to Pm^{147} and Sr^{90}-Y^{90} beta sources. Results were reported for two Si cells coupled to radioactive $Pm_2O_3 \bullet 6H2O$. An efficiency of 0.38 % was achieved based on the total energy released by the beta source (overall efficiency), and 0.77 % if one bases the efficiency on the incident beta flux only. The most extensive work in betavoltaics involved one of the authors. Olsen led an effort at Donald W. Douglas Laboratories in the early 1970's to develop nuclear batteries based on Pm^{147} beta sources coupled to silicon cells [3]. The batteries referred to as Betacels were produced that were characterized by three power levels, 50 , 200 and 400 µW (BOL). The 400 µW Betacel was subjected to extensive safety qualification testing , and was used for powering heart pacemakers. In fact, over 100 units were utilized to power heart pacemakers. The Model 400 battery had a volume of 0.6 in^3 (most of which was shielding) and produced power with an overall efficiency of 1.7 %. Advanced Pm^{147} betavoltaic concepts will be discussed.

Recent Studies – The authors have carried out studies of GaAs cells coupled to Ni^{63} beta sources. Ni^{63} has a 92 year half-life and E_{max} = 67 keV. Betavoltaic power sources based on this isotope would be appropriate for long life batteries with power levels in the µW range. GaAs cells were developed that exhibited very low loss currents, namely, $J_{Loss} < 10^{-7}$ A/cm^2 at 0.5 Volts. In addition to the Ni^{63}/GaAs studies, betavoltaic concepts based on tritium, thallium and Pm^{147} beta sources will be considered.

1. Larry C. Olsen, "Advanced Betavoltaic Power Sources," Proc. 9th IECEC, 754(1974).
2. P. Rappaport, J. J. Loferski and E. G. Linder, RCA Rev. 17, 100(1956).
3. Larry C. Olsen, "Betavoltaic Energy Conversion," Energy Conversion 13,117(1973).

Technical Session 7 - Space Environmental Effects on Solar Cells

N95-70372

p-1

ULTRAVIOLET DEGRADATION TO DOUBLE

ANTI-REFLECTIVE COATED SOLAR CELLS

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Six experiments at COMSAT Labs (since the early '80's) have consistently shown higher UV degradation rates for DAR coated cells when the tests are extended beyond 1000 hours. Results for degradation at 10 years, extrapolated from data at 3000 hours, exceeds 10%. Lesser degradation rates are observed for DAR coated textured cells. Data and models will be presented.

THE RESULTS OF UOSAT-5 SOLAR CELL EXPERIMENT AFTER ONE YEAR IN ORBIT

Christopher Goodbody, DRA, England

N95- 70373

RESULTS OF THERMAL VACUUM TESTS FOR THE PASP PLUS FLIGHT PANELS

p-1

Don Guidice[1], Henry Curtis[2], Mike Piszczor[2], and Paul Severance[1]

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2) NASA Lewis Research Center, Cleveland Ohio

The PASP+ experiment is collection of 16 individual cell strings on 12 different photovoltaic modules, representing a wide variety of cell and array technologies, which will be launched from a Pegasus in early 1993. The main objectives of the experiment are to obain environmental interaction data between the modules and the space plasma; and to obtain radiation damage data on the newer types of cells. The orbit will be about 1050 nautical miles by 190 nautical miles with an inclination of 70 degrees.

During late June and early July of this year, we took the PASP+ panels with all 12 modules and the flight controller to Boeing for a series of thermal vacuum tests. The main objectives of these tests were to verify the thermal balance model of the space experiment; to obtain good data for temperature coefficients of the various modules; and to have an "end-to-end" test of the modules and controller.

We will present data on the module temperatures and the measured temperature coefficients. We shall discuss the limitations of the test setup and some of the assumptions that were made. We shall also present some module performance as a function of temperature.

/-4N 11411

COMPUTATION OF PHOTOVOLTAIC PARAMETERS UNDER LUNAR TEMPERATURE VARIATION

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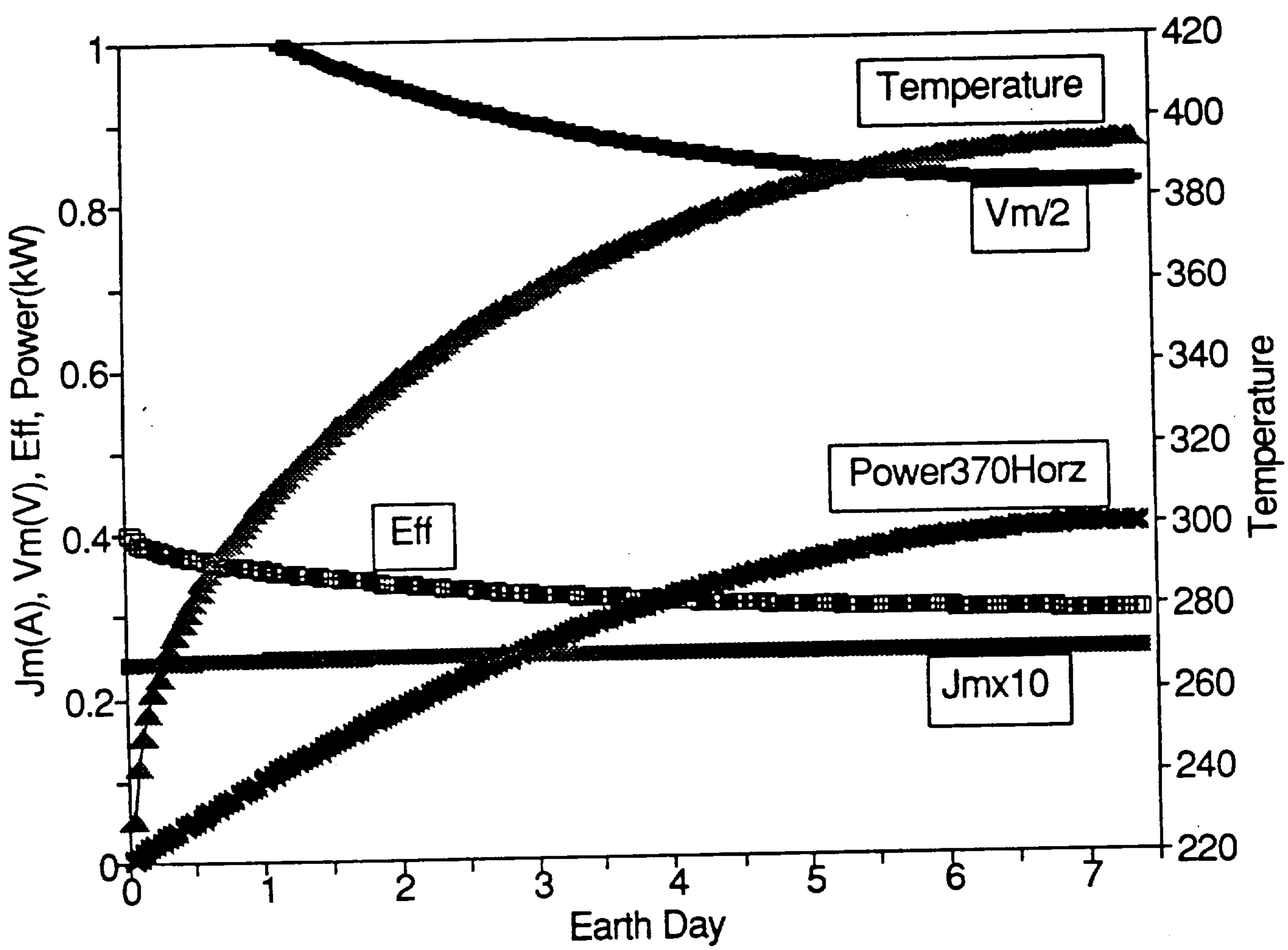
Photovoltaic (PV) arrays with regenerative fuel cell energy storage is a prime, power-system candidate in a lunar base development plan that does not require high power levels initially. The advantages of PV arrays are modularity, lightweight, and a long record of reliable power production in space with a reduced technical risk, however, with the disadvantage of necessitating a storage system for the long (354 hours) lunar night. The PV module performance decreases at higher temperatures. Surface temperature variations of the moon are extreme, the maximum (noon) temperature being ~ 384 K. The present work provides detailed computations of photovoltaic parameters; and calculates the power output of single- and two-junction solar modules under different configurations using an earlier microcomputer-based program for the computation of optimum bandgaps of single- and two-junction solar cells at different temperatures. The program also calculates the necessary PV-array and regenerative-fuel-cell sizes to satisfy stipulated levels of day- and night-time power consumption. Firstly, the program calculates the variation of solar-cell temperatures during a lunar day for three different array configurations viz. horizontal, tracking and triangular. The temperature of the solar cells are different from that of the lunar surface and also are different for the different configurations. The variation of the photovoltaic parameters: short circuit current J_{sc}, open circuit voltage V_{oc}, fill factor FF, and efficiency η of single- and two-junction solar cells through one lunar day for three different configurations of solar cell array are then calculated using the values of the optimum bandgaps provided by the earlier program. Default values are given to some parameters such as top/bottom cell bandgaps, array configuration, day/night power consumption, efficiency of the storage cell for night-time use. However, the values can also be selected by the user. The earlier program has been used to calculate the optimum combinations of bandgaps which will give the highest power output for each of the three configurations. In varying the bandgap values, some of the combination of bandgaps might not be practically realizable. However, the program gives a narrow region of bandgaps which will be the most effective in producing high efficiency solar cells with maximum power output. Top- and bottom-cell bandgaps of 1.83 and 1.2 eV respectively were found to provide the highest power output for tracking and horizontal configurations, while the triangular configuration gives a maximum power output corresponding to top- and bottom-cell bandgaps of 1.78 and 1.15 eV respectively. In the case of the horizontal configuration, the solar-cell temperature variation is similar to the temperature variation of the lunar surface. On the other hand, the temperature of solar cells has a narrower variation in triangular configuration. The optimum bandgaps were found to be strongly influenced by the mean temperature of the cells for each configuration. Figure illustrates the variation of temperature, optimum current (J_m), optimum voltage (V_m), efficiency and power (P) of a solar array installed in the horizontal configuration from lunar sunrise to noon.


Temperature
Vm/2
Power370Horz
Eff
Jmx10
Jm(A), Vm(V), Eff, Power(kW)
Temperature
Earth Day
0
0.2
0.4
0.6
0.8
1
220
240
260
280
300
320
340
360
380
400
420
0
1
2
3
4
5
6
7